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APPLICATION OF WOOD-BASED SEISMIC RETROFITTING TECHNIQUES ON EXISTING TIMBER AND MASONRY STRUCTURES: DESIGN STRATEGIES, MODELLING APPROACHES AND PRACTICAL BENEFITS FOR TWO CASE-STUDY BUILDINGS

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Abstract

Reversible retrofitting techniques for protecting architectural heritage against seismic events have found increasing application in existing or historical buildings. In this framework, the use of wood-based strengthening solutions for both timber and masonry structures has shown promising results, as proved by several recent research studies. Starting from these outcomes, the present work aims at highlighting the potential of such timber-based retrofitting methods from both the academic and the professional perspective, considering two case-study buildings: a stone-masonry church from 18th century with a timber roof, and a Venetian sawmill composed of masonry and timber structural portions. In the first case-study building, the church of St. Andrew in Ceto (province of Brescia, Italy), the lack of joints among the roof timber members and the masonry walls, as well as the in-plane flexibility of the roof structure itself, made the church vulnerable to seismic actions and prone to local out-of-plane masonry collapses. The second case-study building, the sawmill of Vallaro (province of Brescia, Italy), was composed of two building units, one featuring mainly timber structural elements, the other consisting of masonry walls and a wooden roof. This second intervention was very complex, because of the different materials involved, their conservation state, and the need to transform part of the building in a museum, with increased design static and seismic loads. For both case studies, timber-based seismic retrofitting interventions were applied, consisting of the addition of new wooden members, and the use of plywood panels and cross-laminated timber elements. This work presents and discusses the adopted design and modelling strategies, as well as the practical benefits of the applied solutions. The present study can thus contribute to the promotion of timber-based techniques in the combined structural, seismic, and conservation upgrading of existing buildings belonging to the architectural heritage of seismic-prone countries.

Keywords: seismic retrofitting, timber, masonry, architectural conservation, wood-based strengthening.

1. Introduction

Existing or historical buildings that are part of the architectural heritage of several countries, often feature masonry walls as vertical loadbearing structural components, and timber floors or roofs as horizontal elements. With reference to the Italian context, these building typologies are very frequent, and have highlighted significant vulnerabilities from the seismic point of view, as proved by several local or global collapses observed after recent earthquakes [1–3]. The poor characteristics of masonry walls, the lack of adequate connections among vertical and horizontal structural components, as well as the flexibility and insufficient capability of timber floors to transfer and redistribute seismic loads, can be identified as the main causes of such collapses. Hence, the improvement of these characteristics is essential for preserving monumental constructions and the architectural heritage in general, by limiting as much as possible the structural damage induced by earthquakes.

However, when designing seismic retrofitting methods for such buildings, their historical value has to be taken into account as well. The selected interventions have thus to be reversible, not invasive, and enable the architectural conservation of these structures. In this context, timber-based techniques

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constitute a promising, effective opportunity for reversible seismic strengthening and restoration of existing buildings [4–7]. With reference to the improvement of the response of timber floors to earthquakes, research studies on wood-based retrofitting techniques such as the overlay of cross-laminated timber (CLT) [8], oriented strand board (OSB) [9], or plywood panels [10–14], demonstrated the excellent performance and high potential of these strengthening methods. In particular, an overlay of plywood panels fastened around their perimeter to the existing sheathing can greatly increase not only the in-plane strength and stiffness of a wooden floor, but also its energy dissipation, providing additional benefits for the whole masonry building [15–18].

In this work, the application of this strengthening technique to two existing masonry buildings is discussed, highlighting the advantages of a seismic wood-based retrofitting, also from the professional and practical point of view. The case-study buildings consist of the Church of St. Andrews in Ceto and the Venetian sawmill of Vallaro (both located in the mountain area of the Province of Brescia, Italy), and are shown in Fig. 1. After describing the buildings and their vulnerabilities in detail (Section 2), the applied reversible, wood-based retrofitting interventions are discussed (Section 3). The contribution of these strengthening solutions to the seismic improvement of the buildings are analysed, in agreement with the Italian Building Code [19], by means of numerical models, presented in Section 4, where also the specific modelling strategies are discussed. The results from the analyses are presented in Section 5, followed by a detailed overview of the benefits of applying wood-based retrofitting techniques to the two case-study buildings (Section 6), and by the conclusions of this work.

2. Analysed case-study buildings

2.1 St. Andrew's church

The Church of Ceto (Fig. 2), built 1708–26, is a stone masonry building consisting of a single nave measuring 21×14 m, with an average height of 14.5 m, and covered with a barrel vault. The apse has dimensions of 8.2×8.2 m, with an average height of 13 m, and is covered with a cross vault. The building rests on sloping rocky ground and is located on top of a retaining wall. With regard to the main structural components of the church, all walls are composed of stone masonry, reaching an average thickness of about 220 cm in the location of the buttresses, which also feature existing metal ties at the vault height. Elsewhere, the thickness of the walls varies from 70 cm to 100 cm. The roof entirely consists of wooden structural elements (spruce and larch), shown in Figs. 2-3.

Overall, the case-study church did not present issues from the static structural point of view. Several cracks and detachments of material could be observed from the first inspection, but these only involved the finishing layer, and had been caused by the chemical and thermo-hygrometric incompatibility between stone masonry and cement plaster, here improperly applied in past restoration works. The existing metal ties were in good state and well restrained to the walls, and the masonry structural elements appeared to be well dimensioned and constructed.

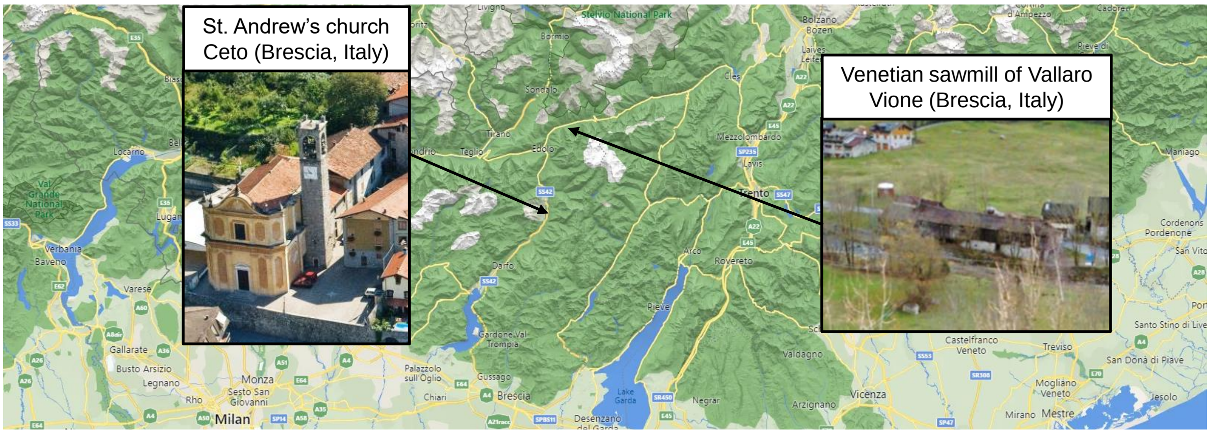

Figure 1. Location and view of the two analysed case-study buildings in the Province of Brescia, Italy.

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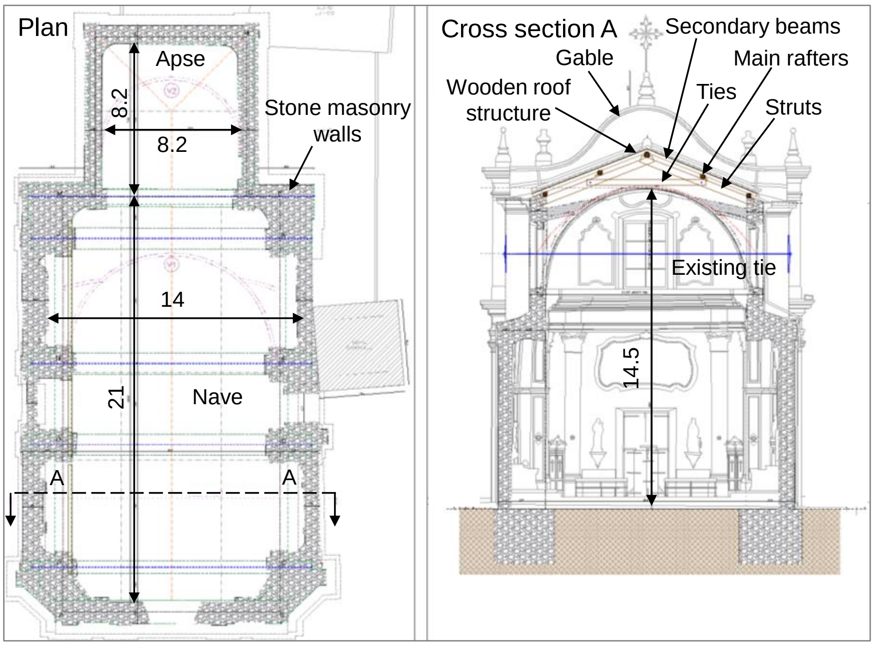
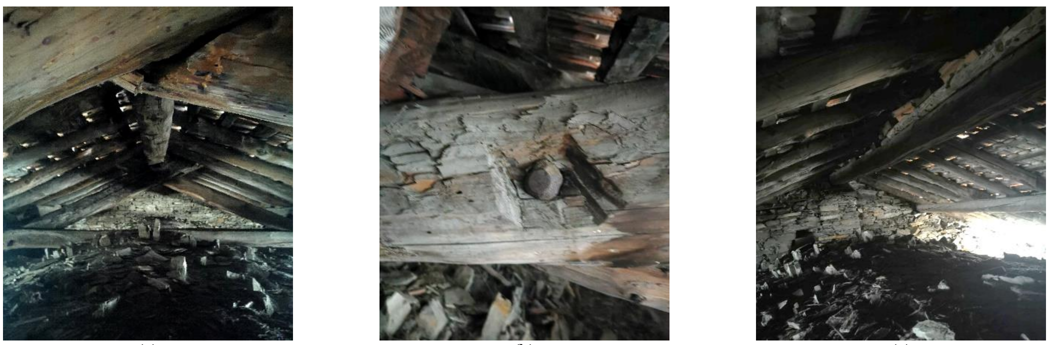


Figure 2. Plan and cross section of the case-study church; dimensions in m.

The wooden roof structure was found in fair state of conservation, but was very difficult to inspect, as the attic of the nave and the apse is narrow and normally not accessible. Most of the roof joists were found in good conditions, only a small number (≈ 15%) were locally affected by biological degradation, mainly due to slight water infiltrations. However, the ridge beam (Fig. 3c) appeared to be very undersized, also considering the spans involved, up to 8 m: large deflections could be observed, which had been compensated over time by additional wooden blocks, to keep the support for the secondary beams as horizontal as possible. The main wooden struts and ties were in a good state, and had adequate dimensions for their structural purpose. Yet, the existing connections with metal pins (Fig. 3b) did not appear to be very effective, and the ties could not fully absorb the thrusts induced by the struts, which seemed thus to be partly taken by the buttresses.

The latter mechanism could be particularly critical in the event of an earthquake, also considering the absence of effective joints among the structural elements of the roof. In other words, the roof would not be able to act as a diaphragm, absorbing the seismic actions and redistributing them to the masonry walls. Besides, effective connections between the timber roof structure and the walls or buttresses were also absent, thus the shear forces induced by an earthquake could not be transferred properly. In light of these findings from the performed inspections, reversible, timber-based seismic retrofitting interventions were designed and applied to the roof, as presented in section 3.



(a) (b) (c)

Figure 3. (a) Existing wooden roof structure; (b) existing metal pin between timber struts and ties; (c) ridge beam undergoing excessive deflection.

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2.2 Venetian sawmill of Vallaro

The Venetian sawmill of Vallaro (Fig. 4), in the municipality of Vione, was built at the end of the 19th century, and has been selected for a full restoration plan in order to transform it in a museum. The building can be subdivided in three independent portions A, B, and C.

- Portion A (280 m^2, Fig. 5a-c) consists of a single-storey timber structure and a stone masonry basement, featuring 50-60 cm thick walls. The ground timber floor is composed of spruce joists and planks, but part of it was strengthened in the past with an incompatible 20-mm-thick concrete slab. The whole wooden roof structure is also made of spruce, and rests on timber columns. The timber members were found in a bad state of conservation.
- Portion B (50 m^2, Fig. 5d) is a two-story stone masonry structure (wall thickness 50-60 cm) with timber floors and roof.
- Portion C (80 m^2) consist of a prolongation of the roof structure of portion A, and was found in bad state of conservation as well.

The existing structure is the result of a series of interventions carried out over time, causing overlapping between original members and elements added later, often incompatible or of low quality. This is the main reason for the poor conditions of the building from the point of view of conservation, with extended degradation phenomena caused by water infiltrations from the roof.

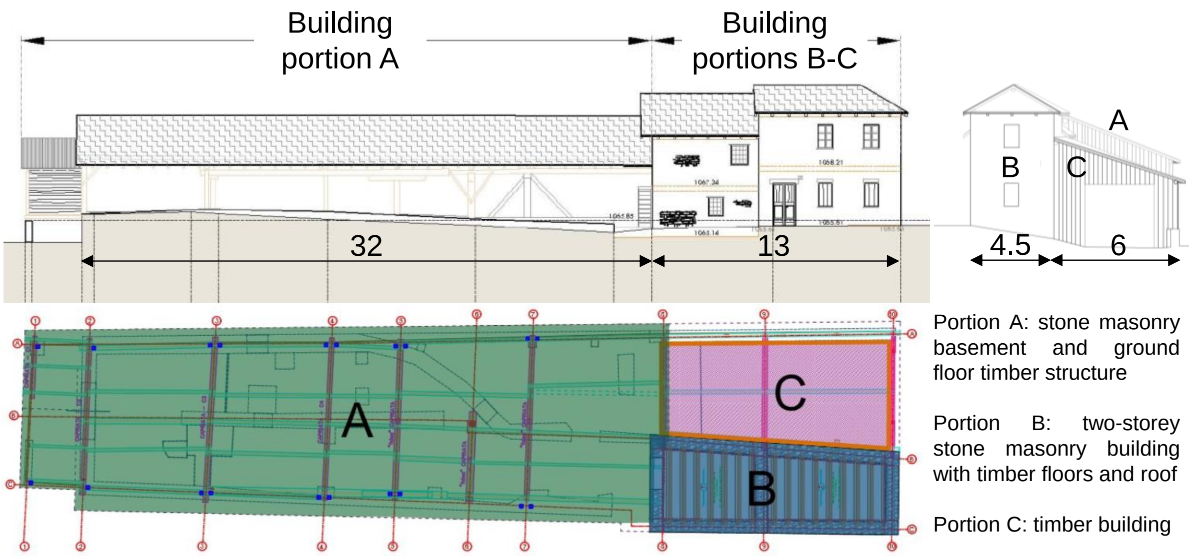

Figure 4. Plan and side views of the case-study sawmill; dimensions in m.

(a) (b) (c) (d)

Figure 5. Front (a), side (b), and interior (c) views of portion A of the sawmill; view of portion B (d).

The main vulnerabilities that were found, were also related to the poor state of the building. Firstly, the whole portion A presented insufficient load-carrying capacity of the wooden columns, with the existing structure able to sustain static actions only because of provisional strengthening members. All wooden floors and roofs were not in good state, and also very undersized for the future increased design loads (snow, wind and crowd). Furthermore, local cracks were detected in the masonry walls of building portions A and B. Finally, all horizontal structural elements were not able to create an effective diaphragmatic and dissipative action against seismic loads, and joints between floors and walls were absent. Therefore, similarly to the church of Ceto, wood-based retrofitting systems were applied for this building as well.

3. Applied timber-based techniques

3.1 General

The retrofitting interventions on the two buildings were subjected to several strict requirements imposed by the Italian Superintendence for Architectural Heritage, especially in terms of reversibility and compatibility with the existing structures. Thus, the use of mostly wood-based solutions was found to be appropriate and effective to strengthen both case-study buildings from the static and seismic point of view.

More specifically, besides the necessary improvement of the static behaviour of the roof in the church of Ceto and of all floors in the sawmill of Vallaro, the applied retrofitting methods were designed in the framework of the seismic upgrading interventions, pursuant to § 8.4.2 of the Italian Building Code [19]. According to the standard, a quantity ζ_E is defined, representing the ratio between the seismic action that can be withstood by the existing structure, and the seismic action that would be considered in the design of a new building in the same site. In terms of peak ground acceleration (PGA), this quantity can be defined as $PGA_{capacity}/PGA_{demand}$. After having evaluated $\zeta_{E,1}$ for the as-built state and $\zeta_{E,2}$ for the building after retrofitting, the requirement of seismic improvement is met when the designed strengthening solutions ensure that $\zeta_{E,2} - \zeta_{E,1} \geq 0.1$ [19].

3.2 St. Andrew's church

In the church of Ceto, adequate connections between timber roof and masonry walls were absent, therefore the construction would very likely develop local overturning mechanisms in the event of an earthquake, and without retrieving its global resistance. Hence, the main retrofitting intervention consisted of transforming the existing roof in a diaphragm. To this end, an overlay of 30-mm-thick plywood panels fastened to the existing sheathing with 4×60 mm Anker nails at 80 mm spacing, was realized (Fig. 6). This solution enables the adequate transfer of seismic forces and the development of the box behaviour of the construction, but without significantly changing the stiffness of the entire building [7]. Besides, this type of diaphragm can also potentially act as dissipative element, absorbing part of the energy imparted by the earthquake by means of the yielding of the fasteners connecting planks and plywood panels [7]. The retrofitted roof could provide a strength of 275 kN per pitch, reached at a maximum deflection of 35 mm, and an initial stiffness of 44 kN/mm, following the design procedures reported in [7, 18]. As an extra safety measure, in addition to the plywood panels overlay, a light bracing system consisting of 5×80 mm S275 steel plates was designed to promptly prevent local overturning mechanisms of the gable, by directly transferring the pertaining shear forces to the buttresses (Fig. 6). On the perimeter of the walls, the steel plates were adequately connected to the existing masonry through M20 anchor bars, enabling the transfer of shear and tensile stresses.

Some of the members of the existing roof structure were also subjected to local wood-based interventions. The few joists and planks damaged by water infiltrations were integrated with newly supplied joists, laid alongside the existing ones, and featuring their same geometry and wood species. For the undersized existing main beams, flexural reinforcements were created, by placing additional wooden beams clamped to the main ones by means of steel plates and screws. These newly supplied beams had again the same geometrical characteristics and wood species as the existing ones.

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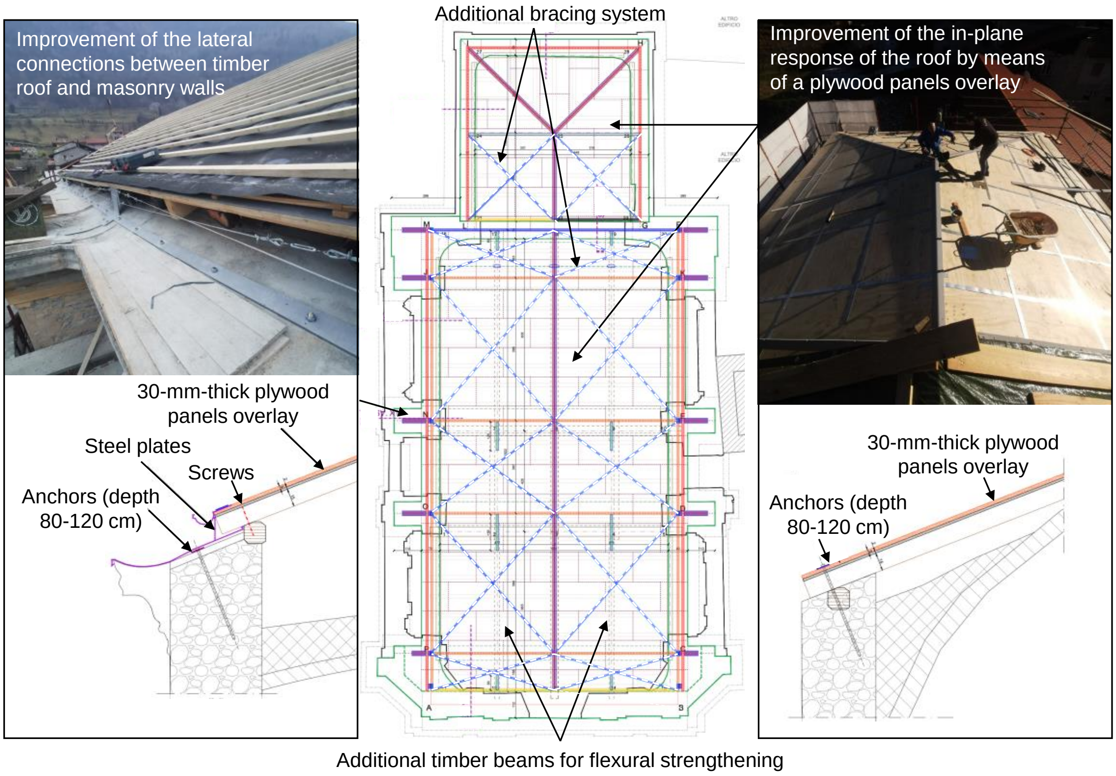

Figure 6. Main strengthening solutions applied to the church of Ceto.

Additionally, screwed joints were created between all secondary joists and the main loadbearing beams, to avoid the possible loss of support due to the vertical seismic component. Likewise, connections between main beams and wooden struts, as well as between the struts themselves and the timber ties, were realized. In this way, besides improving the structural in- and out-of-plane response of the whole roof, it was possible to create an adequate contrast to the aforementioned thrusts induced by the struts, thus beneficially removing this out-of-plane action on the masonry walls.

3.3 Venetian sawmill of Vallaro

The sawmill of Vallaro required several strengthening interventions, not only because of the overall poor conditions of the building, but also in light of the future increased design loads (crowd, snow and wind). Thus, besides the target seismic upgrading, also measures to radically improve the static behaviour of the sawmill were designed. An overview of these interventions is shown in Fig. 7, for all building portions.

For portion A (Fig. 7a), given the low residual load-carrying capacity of the decayed timber columns, newly integrated slender steel elements were designed, along with a new steel frame connected to the strengthened foundations. This allows not only to improve the structural response under vertical loads, but also provides sufficient strength to horizontal actions. In this specific case, in consultation with the local Superintendence, a wood-based solution was not adopted, because it would have required very massive structural elements, which could partly hide the original appearance of the existing building. A timber-based strengthening was, on the contrary, designed to preserve the wooden roof and enhance its structural response. Thus, 12-cm-thick C24 cross laminated timber (CLT) plates, along with additional steel strands were used to improve the static behaviour of the roof, and enable its diaphragmatic action, while contemporarily preserving the existing wooden trusses. Besides, also the ground timber floor was strengthened with 30-mm-thick plywood panels and additional wooden elements. For all realized diaphragms, effective joints with the masonry walls were realized, mostly through S275 or S355 steel angles and M14 or M20 threaded bars. All incompatible past interventions (concrete slabs and elements) were demolished and integrated with new wooden or steel members.

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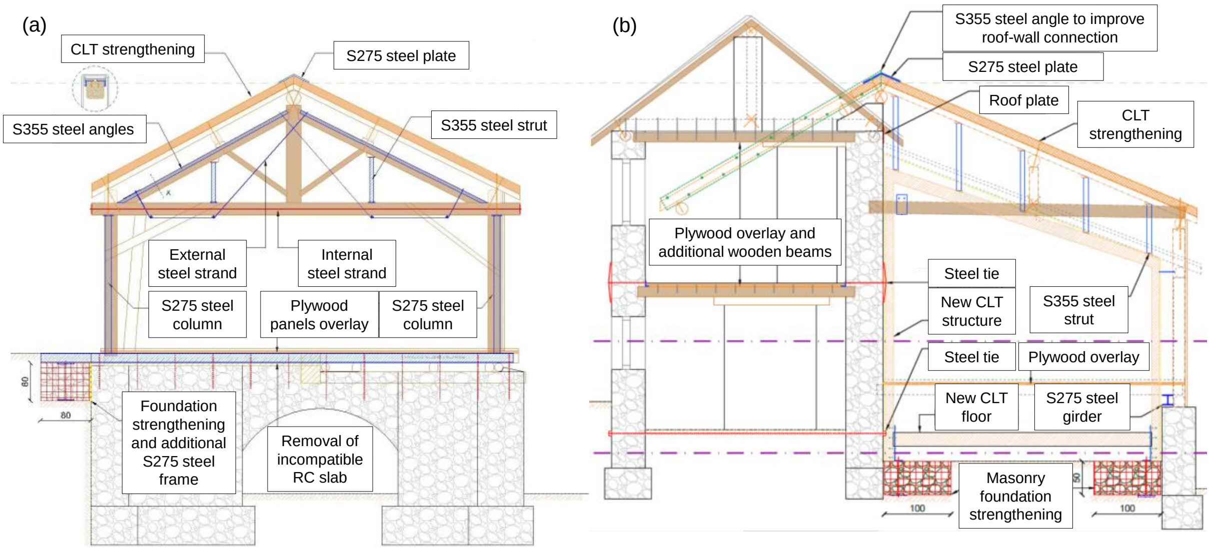

Figure 7. Main strengthening solutions applied to the sawmill of Vallaro: portion A (a) and portions B-C (b).

For portion B (Fig. 7b), flexural strengthening of the timber floors and roofs was necessary. This was realized by means of new wooden beams and a 20-mm-thick plywood panels overlay fastened on them with 6×120 mm screws at 300 mm spacing. Besides, effective connections between horizontal and vertical structural elements were designed, including also new steel ties for an improved confinement of the stone masonry. In portion C (Fig. 7b), these measures were integrated with the realization of an entirely new prefabricated CLT structure, able to support the existing wooden elements, which showed severe decay and excessive lack of load-carrying capacity. These solutions allowed to preserve as much as possible the original appearance and features of the sawmill, despite its bad conditions.

4. Numerical models of the case-study buildings

4.1 St. Andrew's church

For the church of Ceto, a first numerical model was created in the commercial finite element software Aedes.PCM (Fig. 8a). For all walls, the properties for stone masonry suggested by the Italian Building Code [19] were adopted, thus a Young modulus of 870 MPa, a shear modulus of 290 MPa, a compressive strength of 1 MPa, and a tensile/shear strength of 0.018 MPa. Given the overall good state of timber structural members, a C24 strength class was assumed for them. The seismic action for the location of Ceto was prescribed, corresponding to a peak ground acceleration (PGA) of 0.08g.

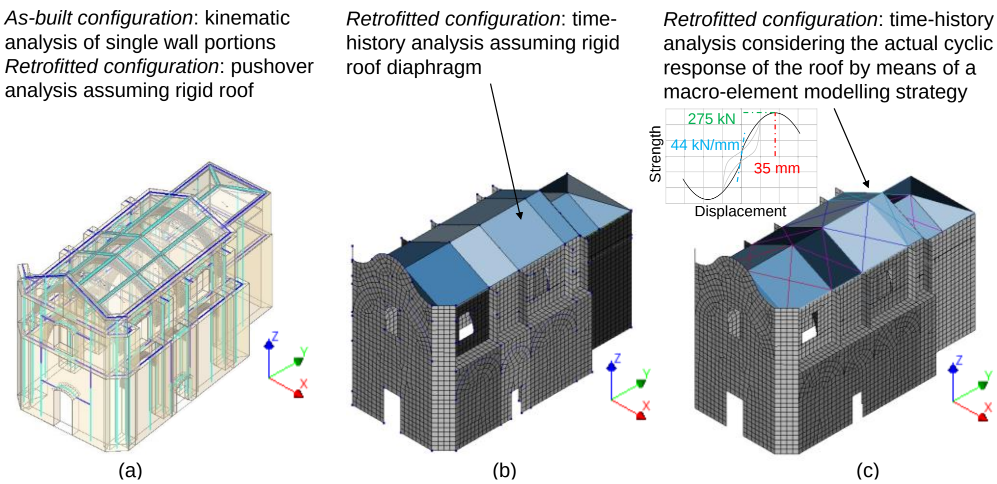

Figure 8. Models of the church in Aedes.PCM (a) and DIANA FEA (b), including cyclic response of roof (c).

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After having specified these properties, the as-built configuration of the church was firstly analysed, evaluating its vulnerability in terms of local collapse mechanisms, as prescribed by the Italian guidelines for seismic assessment of churches [20]. From these investigations, the aforementioned ratio $\zeta_{E,1}$ was determined.

For the retrofitted configuration, with a roof well connected to the walls and able to act as a stiff diaphragm, local mechanisms can be prevented, also given the compactness of the church. Thus, after a modal analysis, a series of 16 pushover analyses were conducted on the whole building in both plan directions, and from the governing curve, the aforementioned ratio $\zeta_{E,2}$ was derived. For these pushover analyses, the control node was taken as the centre of mass of the building, on top of the vault, and the masonry was simulated with an equivalent frame modelling strategy. In order to conservatively not overestimate the displacement capacity of the building, each analysis was stopped as soon as the first pier experienced a drop in in-plane capacity larger than 20% of its strength.

Besides, to validate the use of equivalent frame modelling adopted by Aedes.PCM, a more advanced model was also constructed in DIANA FEA, considering a configuration where the roof was modelled as rigid, similarly to Aedes.PCM (Fig. 8b), and one that also simulated, through a macro-element modelling strategy [7, 17, 18], the full nonlinear, cyclic, dissipative response of the retrofitted roof (Fig. 8c). For all walls, eight-node shell elements featuring the Engineering Masonry Model of DIANA FEA were adopted [21], with the same properties used in Aedes.PCM. Nonlinear incremental dynamic analyses were performed, adopting accelerograms compatible with the design response spectrum for the location of Ceto.

4.2 Venetian sawmill of Vallaro

Two numerical models were realized for the case-study sawmill: portion A was simulated in PRO_SAP software (Fig. 9a), while portion B was once more modelled in Aedes.PCM (Fig. 9b). The first model could be considered as a simulation of an almost entirely new construction, since an adequate response to static and dynamic loads is only provided by newly installed structural elements (CLT and plywood panels, steel members), given the bad conditions of the existing ones. For this case, a modal analysis with response spectrum was performed, considering a behaviour factor of 1.5.

In the second model, instead, an approach similar to St. Andrew's church was adopted, firstly assessing the seismic response of the as-built state through local collapse mechanisms, and then evaluating the improvement in performance after retrofitting, by means of pushover analyses. The modelling assumptions and the properties of masonry and timber were identical to those reported for the church of Ceto. In both cases, the reference PGA for the site was 0.09g, and the floors were assumed as rigid. Portion C was not modelled, because it was a prefabricated structure, directly designed by the supplier.

5. Results

5.1 St. Andrew's church

From the kinematic analysis of the as-built configuration (Fig. 10a), the front façade showed a strong vulnerability, leading to $\zeta_{E,1} = 0.23$ only (PGA at collapse of ≈ 0.02g). It should be noticed that this value can be considered as very conservative, since from the conducted inspections the façade appeared to be well connected to the rest of the structure. Yet, without a roof acting as diaphragm and proper joints, able to redistribute seismic actions among other structural components, similar failure mechanisms could still take place in the event of an earthquake.

With regard to the retrofitted configuration, the modal analyses highlighted a regular dynamic response and close results among the different models: the first fundamental period of the church was 0.47 s in the Aedes.PCM model, 0.47 s and 0.50 s in the DIANA models featuring a rigid and a dissipative roof, respectively. This is coherent with the regularity and symmetry of the church, as well as the proper distribution and arrangement of all masonry piers and buttresses, allowing also the equivalent frame modelling strategy of Aedes.PCM to provide reliable results.

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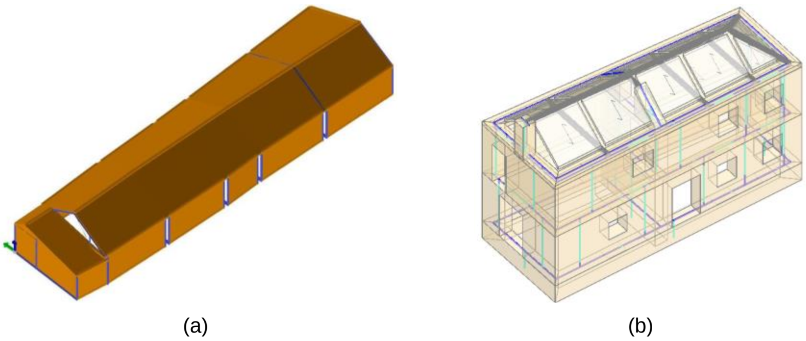

Figure 9. Models of portions A (a, PRO_SAP), and B (b, Aedes.PCM) of the Venetian sawmill of Vallaro.

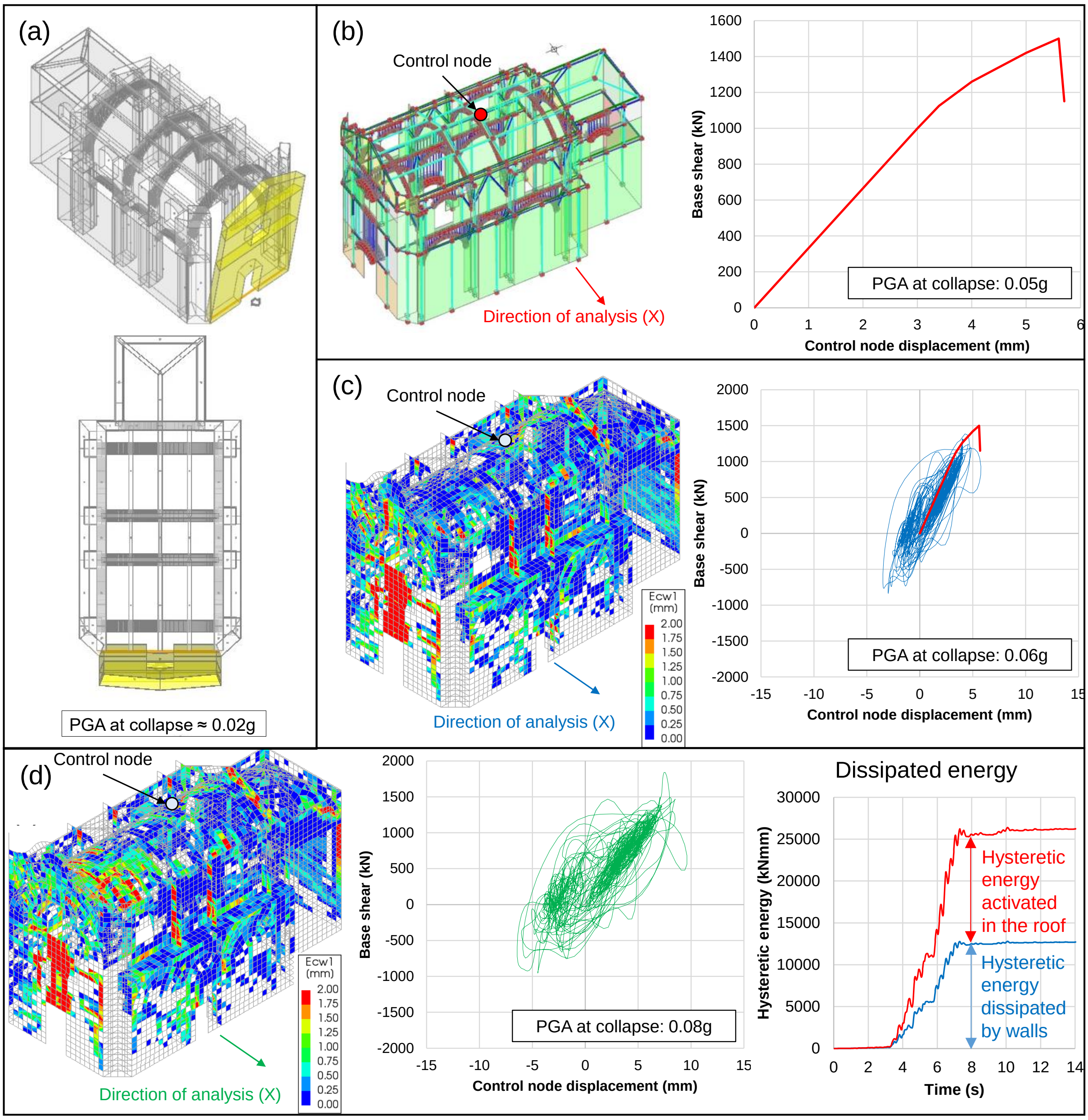

Figure 10. (a) Governing kinematic mechanism of as-built church; (b) governing pushover curve in PCM.Aedes model; (c) crack pattern and base shear-displacement graph from DIANA FEA model with rigid roof, including comparison with pushover curve; (d) crack pattern, base shear-displacement graph and dissipated energy from the model in DIANA FEA featuring the full simulation of the roof retrofitted with plywood panels.

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From the conducted pushover analyses in Aedes.PCM, the governing curve is shown in Fig. 10b, and corresponded to a ratio $\zeta_{E,2} = 0.61$ (PGA at collapse of ≈ 0.05g). It should be noticed that this value represents a lower bound for the seismic performance of the church after retrofitting, because of the conservative assumptions behind the conducted analyses (see Section 4.1). Yet, the requirement of seismic upgrading according to [19] is already met, since $\zeta_{E,2} - \zeta_{E,1} = 0.38 >> 0.1$. Thus, the applied interventions allow to greatly improve the structural behaviour of the building, from both static and seismic perspective.

Similar results (PGA at collapse ≈ 0.06g) were obtained from the time-history analyses in the DIANA model with rigid roof (Fig. 10c), confirming once more that for this case-study also the simplified approach of PCM.Aedes could be sufficient for a correct assessment of the influence of the retrofitting. However, both models cannot capture the beneficial energy dissipation provided by the plywood panels overlay, as highlighted by Fig. 10d, showing the DIANA model where the full cyclic response of the roof was included. When this is also taken into account, the church could potentially survive the on-site design earthquake, and the energy dissipated in the roof could be associated to an equivalent damping ratio of 0.12-0.13 for this case, beneficially reducing the actions that are transferred to masonry walls.

5.2 Venetian sawmill of Vallaro

The retrofitting solutions applied to portion A allowed the new structure to efficiently withstand the expected future design static and seismic loads, for both the additional steel elements and the existing and additional timber members, with unity checks up to 0.95 and a first fundamental period of 0.20 s. Thus, the choice of slender elements allowed portion A to perform as a fully new construction, while keeping as much as possible its original appearance.

More interesting is the case of portion B (Fig. 11), which in the as-built state would be able to withstand less than half of the design PGA ($\zeta_{E,1} = 0.45$) due to out-of-plane walls overturning. After retrofitting, the building could fully withstand the future static actions, while providing an enhanced box behaviour (first fundamental period of 0.13 s). Yet, the retrofitted structure did not show significant ductility, because of the choice of terminating the analysis once in a single masonry elements the shear capacity decreased more than 20% of the peak strength. This allowed not to overestimate the displacement capacity, given the overall bad conservation state of the building. Nevertheless, the requirement of seismic upgrading according to [19] was still met, since $\zeta_{E,2} - \zeta_{E,1} = 0.63 - 0.45 = 0.18 > 0.1$. It should be noticed that, considering the conservative assumptions at the basis of the model, and the additional energy dissipation that is provided by the retrofitted timber diaphragms, the actual expected improvement could be much larger. Yet, given the initial poor conditions of the existing structure, the designed interventions could still lead to a safer, renovated environment for hosting a museum.

6. Practical benefits of the applied wood-based seismic retrofitting techniques

The timber-based retrofitting solutions applied to the case-study buildings are all reversible interventions, and compatible with the existing structural members, which could be effectively strengthened and protected: thus, the adopted retrofitting methods also enable the conservation of the two buildings. Besides, all floors and roofs can now act as diaphragms and prevent local (out-of-plane) collapses of masonry walls, allowing the buildings to develop a box behaviour against seismic actions. The additional plywood panels overlay fastened to the existing sheathings constitutes a reversible, not invasive intervention, which does not excessively increase mass and stiffness of the floors, and potentially enables additional ductility and energy dissipation, as proved in the conducted numerical analyses.

The applied retrofitting methods are not only convenient in terms of seismic improvement, but also from a more practical point of view. The designed solutions were particularly appreciated by both the Curia of Brescia and the Superintendence for Architectural Heritage, as the historical and architectural value of the buildings was preserved. The reasonably low impact on the constructions, linked to a large improvement in their structural properties, is surely a first point of strength of the use of wood-based techniques in these case-study buildings.

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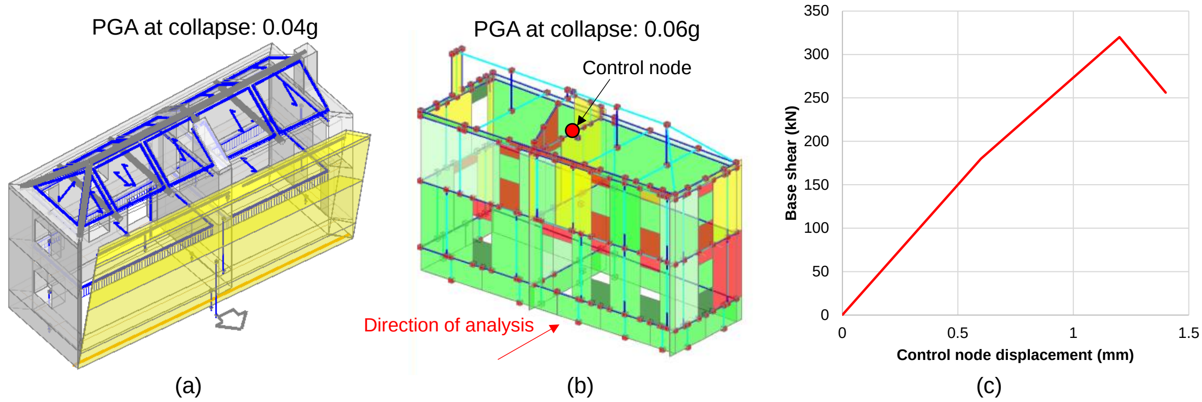

Figure 11. Governing kinematic mechanism of as-built configuration of portion B (a); results from governing pushover analysis in terms of damage on piers and spandrels (b), and load-displacement curve (c).

Besides, from the perspective of professional engineers, these interventions can be efficiently designed and are particularly affordable. The overlay of plywood panels is a very cost-effective measure, and could be realized within the limited budgets available. This result was possible not only because of lower material costs compared to other solutions, but also due to the fast and manageable application of the intervention. For instance, for the church of Ceto, the whole plywood panels overlay was fastened to the existing roof by a local building enterprise composed of only three employees within a single working day.

7. Summary and conclusions

This work has presented the application of several wood-based seismic strengthening techniques on two case-study buildings, St. Andrew's church in Ceto and the venetian sawmill of Vallaro, both located in the Province of Brescia, Italy. The design choices, modelling approaches, and practical benefits of these retrofitting solutions were discussed throughout the paper.

For both structures, local out-of-plane collapses of masonry walls were very likely in the as-built state for already very low seismic actions. Hence, wooden floors and roofs were strengthened with a plywood panels overlay (or CLT for the sawmill of Vallaro, which was in poorer conditions and also needed a static strengthening); the new diaphragms were also well connected to the walls, in order to prevent local failure mechanisms and ensure the development of a proper box behaviour.

The benefits of wood-based solutions have been highlighted from both the seismic and the practical perspective, focusing on their reversibility, lightness, as well as cost- and execution effectiveness. In particular, after retrofitting, a great increase in seismic performance of the buildings can be obtained: the outcomes from the conducted numerical analyses show that the strengthened structures could potentially be able to almost or fully withstand the expected seismic actions on their site, because of the improved box behaviour and additional energy dissipation provided by the strengthened floors.

The results obtained within the analysis of these case-study buildings can contribute to further highlight the benefits of timber-based retrofitting techniques, and to support the research framework promoting their use for the preservation of architectural heritage in seismic-prone countries.

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